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Comparative Energy Analysis from Fire Resistance Tests on Combustible versus Non-Combustible Slabs

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Abstract

Standard fire resistance tests have been used in the design of structural building elements for more than a century. Originally developed to provide comparative measures of the level of fire safety of non-combustible products and elements, the recent resurgence in engineered timber construction raises important questions regarding the suitability of standard fire resistance tests for combustible structural elements. Three standard fire resistance floor tests (5.9 m x 3.9 m in plan), one on a concrete slab and two on cross-laminated timber (CLT) slabs, were undertaken to explore some of the relevant issues. The fuel consumption rate within the furnace was recorded during these tests, and the energy supplied from this was determined. An external fuel supply (from natural gas supplied to the furnace) equating to approximately 3 MW was recorded throughout the concrete test, whereas this was about 1.25 MW throughout the CLT tests. The total heat release rate was calculated using Carbon Dioxide Generation calorimetry; this yielded values of approximately 1.75 MW during the CLT tests (i.e. an additional energy contribution of approximately 0.5 MW from the timber). This demonstrates that considerably more energy input (by about 1.25 MW) was needed to heat the system when the test sample was non-combustible. A further series of six large-scale compartment fire experiments (6 m x 4 m x 2.52 m) was undertaken to further explore comparative performance of combustible versus non-combustible construction when the external fuel load is kept constant and is governed by more realistic compartment fire dynamics. For a fuel-controlled case, the peak temperatures in the compartment with an unprotected CLT ceiling were approximately 200°C higher than in the compartments with a concrete ceiling, whereas for a ventilation-controlled case the compartment with a CLT slab ceiling displayed a burning duration that increased by approximately 15 min. Potential implications for standard fire resistance testing of combustible specimens are discussed.

1. Introduction and Background

For more than a century, standard fire resistance test methods such as ASTM E119 [1] and ISO 834 [2] have formed the foundation of prevailing structural fire engineering approaches. Fire safety regulations and guidance internationally prescribe required “fire resistance periods” for building elements – this is typically defined as the duration during which an element is able to withstand exposure to a standard temperature-time curve within a standard fire resistance testing furnace – with failure criteria defined by loss of load bearing or (notionally) fire separating functions. Despite significant advances in fire science and engineering during recent decades, such standard fire resistance assessments and requirements remain substantively unchanged since these methods were originally developed (notwithstanding some minor changes and additions – for instance the furnace pressure was not initially regulated, and more recently both ISO 834 [2] and EN 1363-1 [3] require that the furnace be controlled using plate thermometers – although ASTM E119 [1] does not utilise plate thermometers).

Structural engineered timber elements (such as cross-laminated timber (CLT) or glued-laminated timber) are increasingly specified in construction. Since timber is combustible, upon exposure to sufficient heat will pyrolyse, and may ignite, and burn, thus contributing additional energy (i.e. heat release) to a fire. This renews the discussion [4]around the fundamental applicability (and engineering meaning) of the conventional 'standard fire resistance' regime for assessing the structural fire response of combustible building elements.

The noted testing programme has generated a wealth of useful comparative data. The current paper focuses on the implications of these additional energy contributions for standard fire-resistance testing and the resulting outcomes for both combustible (CLT) and non-combustible (concrete) structural elements.

2. Experimental Programme

The 'Epernon Fire Test Programme' is an experimental campaign aimed at studying the effects of different fire exposures, both standard and realistic, on two basic types of loaded structural floor slabs, one made from fully exposed cross laminated timber (CLT), and one made from reinforced concrete. These two types of slabs were tested both in standard fire resistance tests *and* in compartment fire tests with varying ventilation factors at CERIB in Epernon, France. Described in this article are three essentially identical standard fire resistance (furnace) tests, carried out in a floor furnace according to the EN 1363-1 [3] standard temperature-time curve; two on exposed CLT slabs, and one on a reinforced concrete slab. Both CLT and concrete slabs were 5.9 m x 3.9 m in plan dimensions. The concrete slab had a thickness of 180 mm, while the CLT slab was 165 mm thick. These thicknesses were selected in an attempt to ensure that the respective slabs were as representative as possible of those that would exist in practice in comparable real buildings, given competing design considerations regarding both ultimate and serviceability limit states at ambient temperature.

The CLT slab was made from spruce wood obtaining strength class C24, and consisted of five uniform lamellae of thickness 33 mm, resulting in a total thickness of 165 mm. The lamellae were joined together using a polyurethane based adhesive, PURBOND HB S709. The concrete slab consisted of C35/C45 concrete of density 2400 kg/m^3, with 8 mm diameter steel rebar net with a mesh size of 100 x 100 mm^2. The cover was 20 mm. All slabs were stored in an air conditioned room set at 23°C for at least 90 days prior to testing. Moisture contents were then measured by placing samples in an oven at 105°C until mass loss was less than 0.1%/day.

2.1. Instrumentation

All slabs were instrumented with in-depth thermocouples, as shown in Figure 1. A total of 44 in-depth thermocouples (including 4 at the exposed surface and four at the unexposed surface) were installed at four different plan locations in the CLT slabs. Thermocouples were inlaid during fabrication of the CLT panel, and drilled into the layers as necessary (Figure 1(left)). A total of 45 in-depth type K thermocouples of diameter 1.5 mm (including five at the exposed surface) were installed at five different plan locations in the concrete slabs. Each location included two thermocouples mounted on the tensile reinforcing steel.

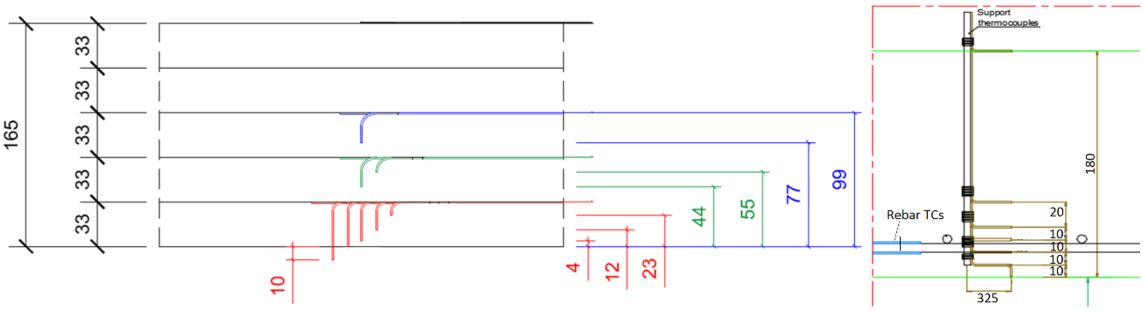

Figure 1: Thermocouple layout for CLT panels (left) and concrete slabs (right). All dimensions in mm.

Furnace temperatures were measured (and controlled) using plate thermometers (after EN 1363-1).

Oxygen, carbon dioxide, and carbon monoxide were measured within the furnace exhaust to allow for later gas analyses. Exhaust flow velocities and temperatures were also measured, as was the mass rate of furnace fuel supplied (natural gas in this case) to the furnace. This allowed a direct analysis of the differences in fuel consumption when testing structural elements made from combustible versus non-combustible materials (in this particular configuration).

3. Energy Analyses

The energy supplied in a standard furnace test can arise from one of two sources: (1) the natural gas being supplied to the furnace burners (which will normally supply the bulk of the energy), and (2) combustion of the test sample itself (in cases where combustible materials are heated sufficiently and release pyrolysis products into the testing chamber). What follows is an approximate analysis of these respective energy contributions.

3.1. Natural Gas Consumption

To generate the temperatures required during a standard furnace test, a fuel (typically natural gas or propane) is premixed with air and injected into a fire testing furnace. The rate of fuel supply is controlled so that the temperature within the furnace matches a prescribed target standard temperature-time curve.

The time-history of natural gas consumption required to produce the standard temperature time curve within the fire testing furnace during the three tests undertaken during the current study is shown in Figure 2 for the first 120 minutes of these tests. During this time, the test on the concrete slab consumed almost three times as much external fuel (natural gas) than did the tests on exposed CLT slabs, despite the same furnace temperatures being recorded during both tests (as measured using plate thermometers).

It should be noted that the increased gas consumption in the concrete test corresponds to a proportionate increase in the amount of air injected into the furnace. A full analysis would include this factor, however this has been estimated to be on the order of 100 kW (by multiplying the temperature change of the air by its mass and specific heat capacity), and is thus negligible for the analyses undertaken herein.

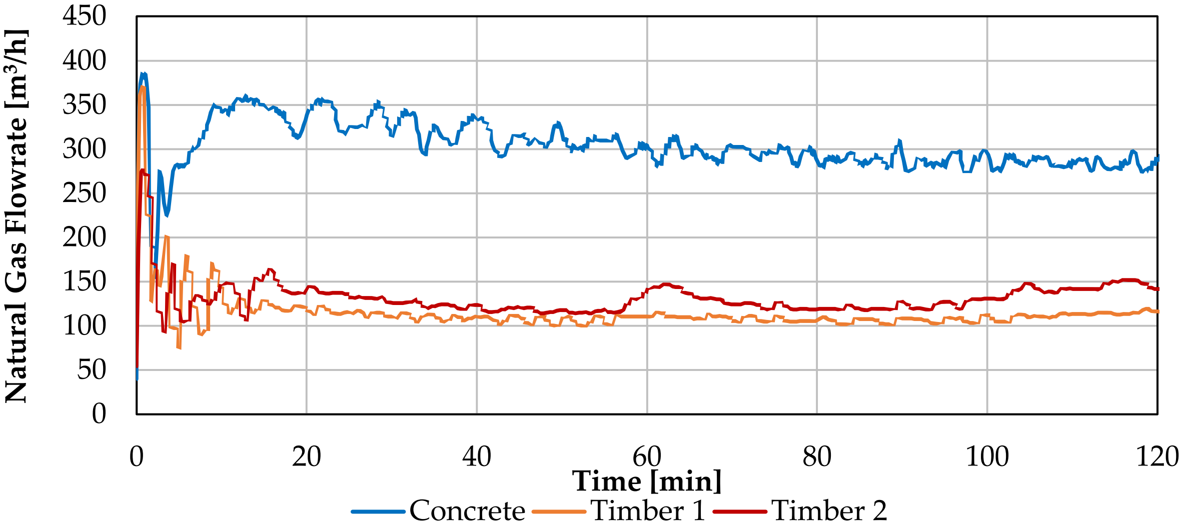

Figure 2: Natural gas consumption recorded during furnace tests on concrete and cross-laminated timber slabs.

Assuming that combustion of the natural gas occurs within the furnace control volume (considered a reasonable assumption by the authors), the energy contribution from the natural gas burners can be approximated from the mass flow rate and the known heat of combustion of natural gas. The constituents of the natural gas were known in this case, and thus its properties can be approximated. The gas in the current tests was about 93% methane, 4% ethane, and 3% other gases. The heats of combustion can be obtained from Tewarson [5] and the heat of combustion of the natural gas, ΔH_c, was determined as a weighted average of its constituents. This yields a heat of combustion of approximately 47.8 kJ/g, with slight variation between tests (this has accounted for in the analysis presented). The heat release rate (HRR) can thus be calculated as:

$$\dot{Q}_{NG} = \rho \chi \Delta H_c \dot{V} \tag{1}$$

where ρ is the density (calculated from the gas make-up, typically around 0.72 kg/m^3), χ is the combustion efficiency (assumed to be unity due to the natural gas being pre-mixed with air – this is confirmed by a lack of CO measured in the exhaust for the concrete test), and $\dot{V}$ is the volumetric flow rate.

During the first 120 minutes of these tests, this gives the heat release rate curves shown in Figure 3. It is notable that this plot shows only the heat release rate contribution from the natural gas burners, and it does not (yet) consider any additional energy released by combustion of the timber.

It is clear that major differences (~350% in this case) exist in the external energy provided to the furnace control volume when testing a concrete slab as compared to a CLT slab according to EN 1363-1 in the floor test configuration of the current study.

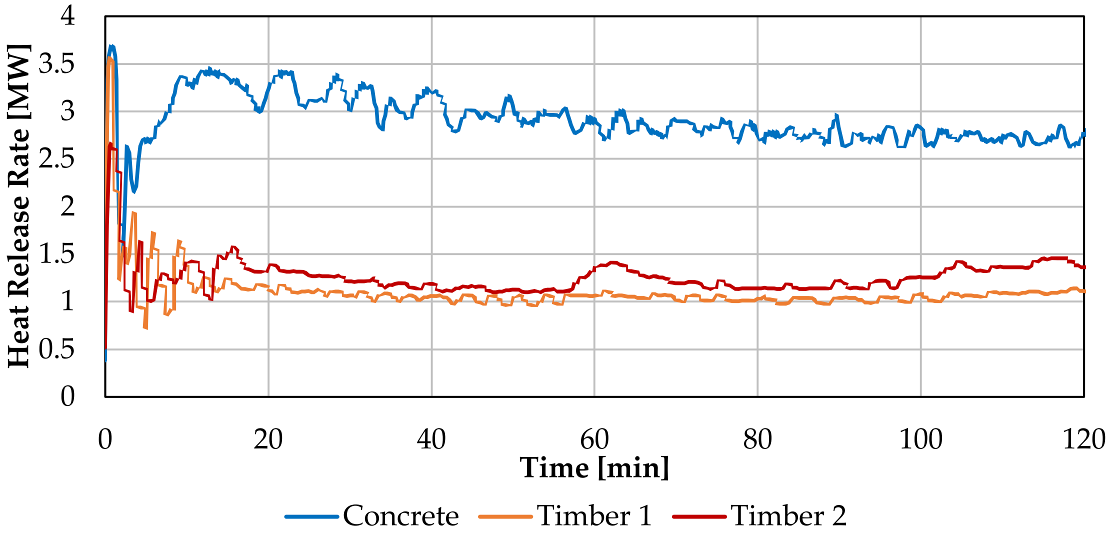

Figure 3: Comparison of heat release rates approximated from natural gas supply in standard furnace tests on concrete and cross-laminated timber slabs.

The total energy inputs from the natural gas burners (over 2 hours of fire testing) were 7957 MJ and 9078 MJ for the two tests on CLT slabs, whereas this was 20954 MJ for the test on the concrete slab.

It is immediately evident that, in a standard fire resistance test assumed to give an equivalent thermal exposure, a considerable difference exists in the external energy provided. This physical reality has potentially important consequences for the comparative performance of timber versus non-combustible structural elements in real fires, and calls into question the fundamental bases of the conventional fire resistance framework based on durations of 'fire resistance'. It might be the case that different types of structures should be required to meet different fire resistance benchmarks when designs are justified on the basis of standard furnace testing, or indeed that application of the 'fire resistance' framework should be abandoned in favour of a more rational, risk-based fire engineering design approach intended to deliver the requisite (agreed) level of safety.

3.2. Calorimetry Analyses

Calorimetry is an approach commonly used within fire science to approximate the total energy released during a fire. Calorimetry typically assumes a fixed value for the energy released per unit mass of oxygen consumed by combustion reactions (in the case of oxygen consumption (OC) calorimetry), or per mass of CO and CO_2 released (in the case of carbon dioxide generation (CDG) calorimetry).

Due to the premixed nature of the fuel supply in the tests herein, OC calorimetry is not appropriate, as OC calorimetry relies on depletion of oxygen from atmospheric concentrations. Using the CO and CO_2 concentrations measured in the exhaust, however, the *total* HRR (i.e. from the natural gas *and* the test sample) can be approximated using CDG calorimetry [5].

Hidalgo [6] provides an expression for this approach as follows:

$$\dot{Q} = \frac{\dot{m}_e}{M_a}\left(1 - X_{H_2O}\right)\left(E_{CO_2}M_{CO_2}X_{CO_2} + E'_{CO}M_{CO}X_{CO}\right) - \frac{\dot{m}_e}{M_a\left(1 + \phi(\alpha - 1)\right)}\left(1 - X_{H_2O}\right)E_{CO_2}M_{CO_2}X_{CO_2,a} \tag{2}$$

where $\dot{m}_e$ is the mass flow rate in the exhaust, M is the molar mass, E is the energy released per unit mass of CO_2 generated, X is the molar concentration, ϕ is the oxygen depletion factor (reasonably assumed here to be equal to one), and α is the volumetric expansion factor, taken as 1.105 [7]. Molar masses for the relevant gases are 44 g/mol for CO_2, 28 g/mol for CO, and 29 g/mol for air [6]. From Tewarson [5], E_{CO_2} = 15.3 kJ/g for methane, and 9.5 kJ/g for Douglas fir (assumed to be applicable to the CLT used in the current tests). As with the heat of combustion, weighted averages of these values were calculated based on the composition of the natural gas for each test; this gave $E_{CO_2} \approx$ 17.3 kJ/g. E'_{CO} can be calculated from Hidalgo [6]:

$$E'_{CO} = \frac{E_{CO_2}M_{CO_2} - \Delta H_{CO\rightarrow co_2}}{M_{CO}} \tag{3}$$

where $\Delta H_{CO\rightarrow co_2}$ is the energy released in the complete combustion of one mole of carbon monoxide (producing carbon dioxide), equal to 283 kJ/mol. This gives around 17.0 kJ/g for natural gas, and 4.8 kJ/g for timber.

This approach yields the HRR data shown in Figure 4 for concrete, where they are compared with the values previously obtained based on natural gas consumption. A 300-point LOESS smoothing algorithm was then applied to the CDG data to remove noise. While data are not available beyond 30 minutes due to problems with the exhaust flow measurements during the concrete tests, it is evident that the two approaches show excellent agreement whilst data are available.

3.2.1. Timber Contribution

Further to the energy supplied by the burners inside the furnace, when a combustible material (such as timber) is being tested, it will ignite and contribute additional energy if the oxygen content is high enough in the furnace. When timber is exposed to heat, it will begin to pyrolyse, releasing flammable gases. When these gases mix with enough oxygen, and with sufficient energy (either from a pilot flame, or through a sufficiently high gas temperature), gas-phase ignition will occur, resulting in flaming. This combustion will release additional energy.

To calculate this contribution, it is necessary to know how much CO and CO_2 is produced by the natural gas, and how much is produced by the timber, due to the large differences between the E_{CO_2} values. Due to the premixing of the natural gas, it was assumed that no CO is produced by the combustion of the natural gas; this is verified by the concrete test (in which only natural gas was burning), in which no CO was recorded. Therefore, assuming complete combustion of the natural gas, the CO_2 contribution can be calculated from stoichiometry. The difference between the measured CO_2 concentration and the calculated CO_2 contribution from the natural gas is thus the CO_2 contribution from the timber. Carbon Dioxide Generation calorimetry can thus be undertaken on these values to determine the timber HRR (and thus the total HRR through summation). These values are shown alongside the concrete HRR in Figure 4. The CLT contribution alone is shown in Figure 5. It should be noted that the CLT continues to burn at an approximately constant rate throughout the tests (after build-up of an initial char layer); this is attributed to continuous, localised delamination which occurred throughout.

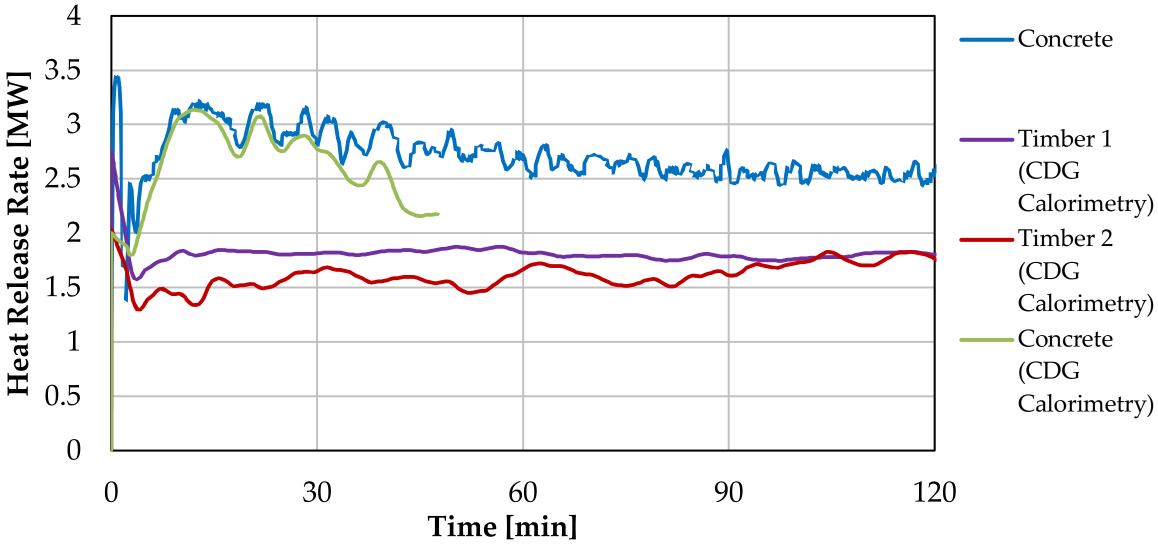

Figure 4: Comparison of CDG and natural gas consumption HRR for concrete furnace test and comparison of total heat release rates for all three tests.

The contribution from the CLT, as calculated by CDG calorimetry using the measured CO concentrations, and the CO_2 generation calculated as described above, is shown in Figure 5.

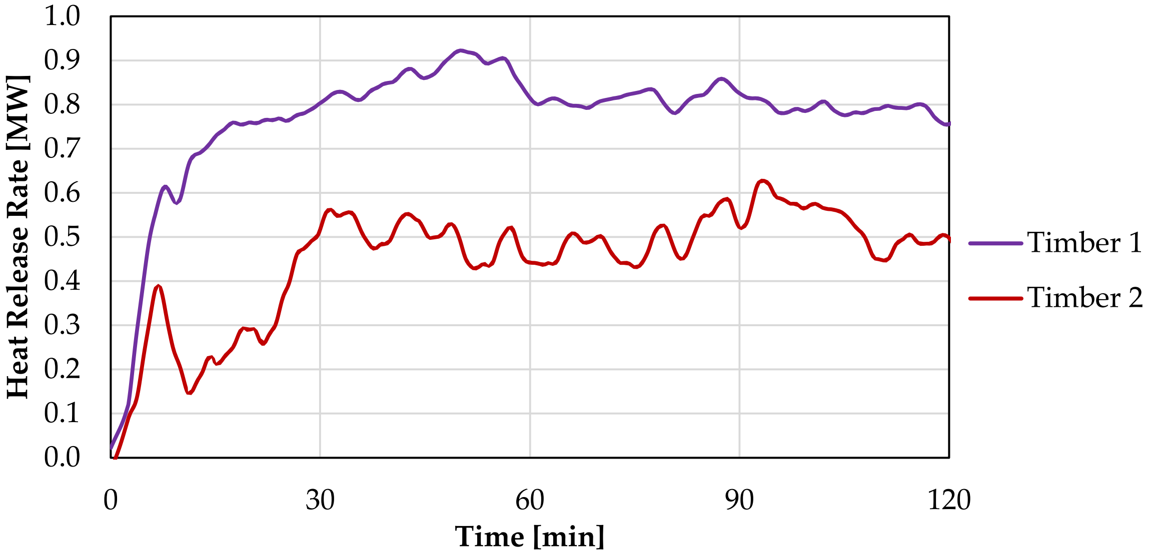

Figure 5: Contribution from burning of CLT in the two standard fire tests conducted.

The first timber sample provides approximately 0.8-0.9 MW of heat throughout the test, whereas the second sample provides approximately 0.5-0.6 MW. This is a significant difference between the two tests (approximately 50%), despite the energy provided by the natural gas being very similar between the two tests. This difference can be partially attributed to the variability of a natural material such as timber, as well as the stochastic nature of delamination, which can result in unpredictable and often very different behaviour from apparently identical test specimens [8].

3.3. Absorbed Energy

The energy absorbed by each test specimen can be calculated as:

$$\dot{q}''_{abs} = \sum_{i=1}^{n} d_i \rho_i C_{p,i} \Delta T_i \tag{4}$$

where n is the number of in-depth thermocouples at each location, d_i is the depth of sample associated with each thermocouple, $C_{p,i}$ and ρ_i are the specific heat capacity and density of the sample, taken as a function of temperature (and thus implicitly accounting for phenomena such as moisture migration) from the thermal properties given in Annex B of Eurocode 5 [11] for timber, and in Eurocode 2 [12] for concrete. The properties were based on the moisture contents recorded prior to the tests – 5.1% for concrete, and 11.1% and 11.0% for the first and second timber tests, respectively. The temperature profiles for timber and concrete are shown in Figure 6, with each measurement depth averaged across all the thermocouple "bundles".

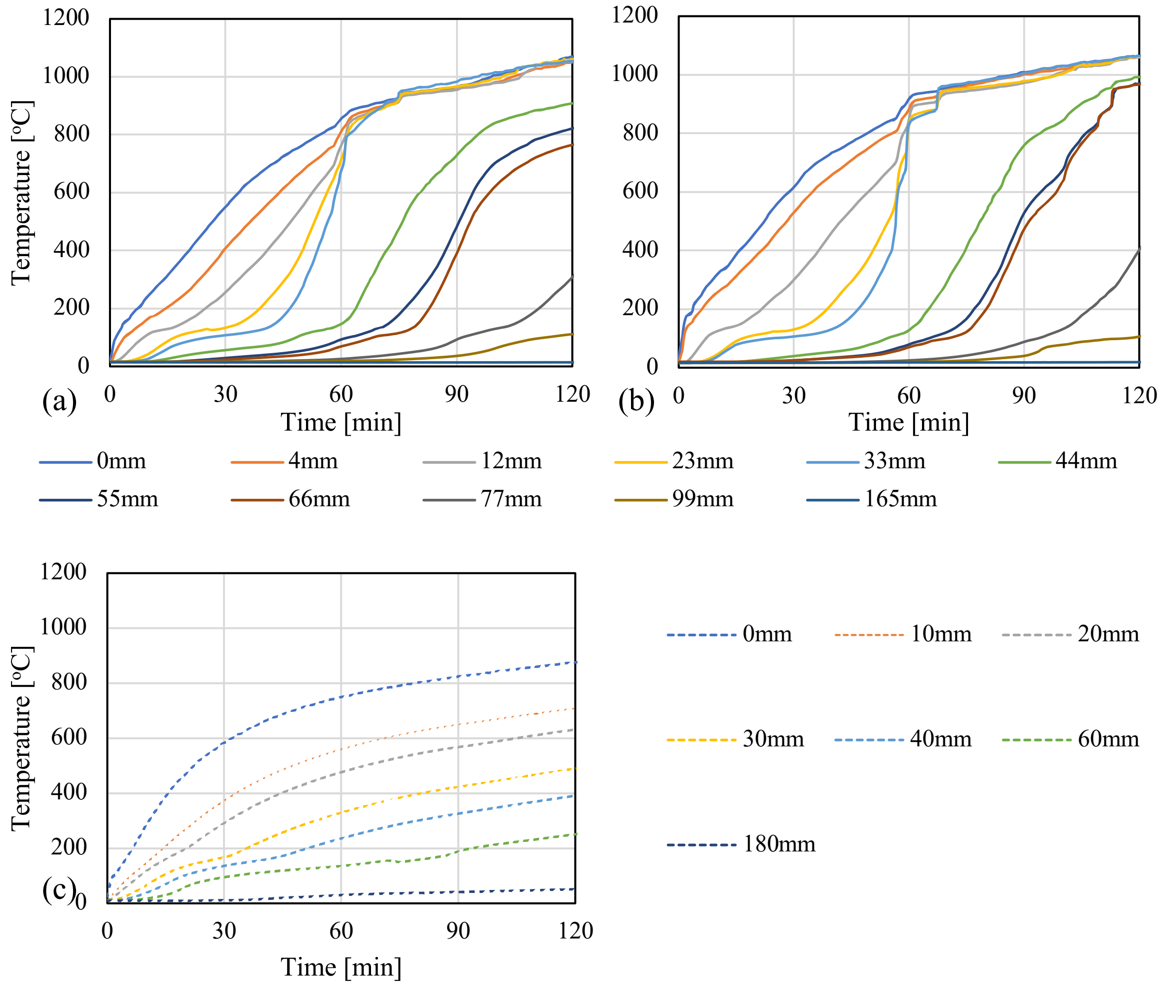

Figure 6: In-depth temperature measurements averaged across all measurement locations for (a) 1st timber furnace test, (b) 2nd timber furnace test, and (c) concrete furnace test.

This gives the absorbed energies (summed/averaged across the four/five measurement locations) in Figure 7.

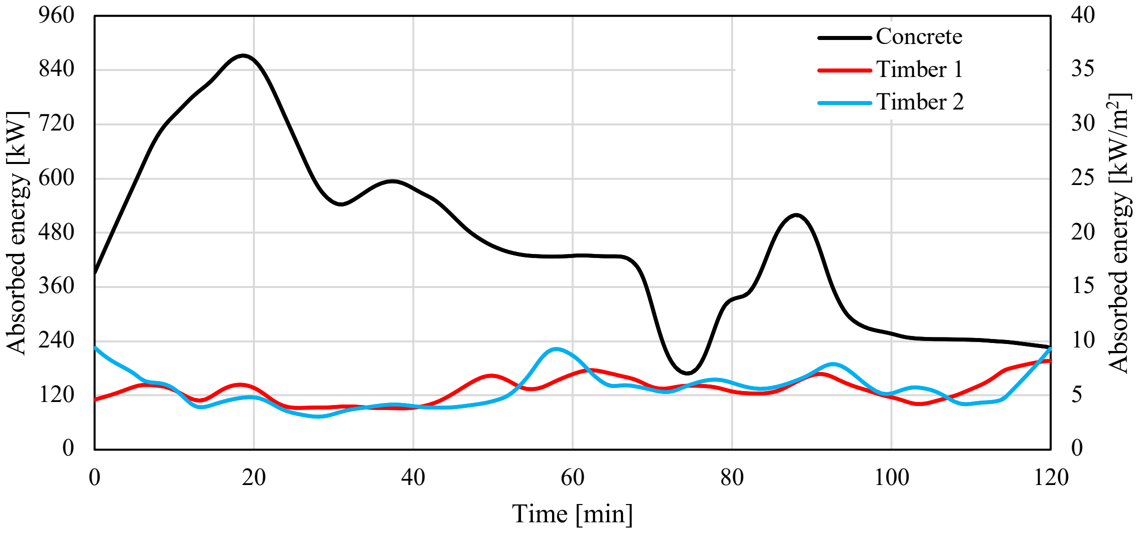

Figure 7: Energy absorbed by test specimens.

Good agreement can be seen between the two timber experiments, however it is clear that much more energy (~3.5x) is absorbed by the concrete sample.

A comparison of the energy data between different tests is shown in Figure 8. It is evident that more energy is provided in a test on concrete, even if the additional energy contributed by the timber is considered. The difference in the energy absorbed by the sample is even more significant, as discussed above. However, in both cases, this is a comparatively small proportion (~17% for concrete, 7-8% for timber) of the total energy supplied to the furnace. This is likely due to the differences in thermal diffusivity between concrete and timber, which results in less energy being absorbed into the timber specimens than those made from concrete. Given the uncertainty around several of the measurement techniques, it is not possible to provide meaningful estimates of error bounds, but clearly the values provided have some error associated with them.

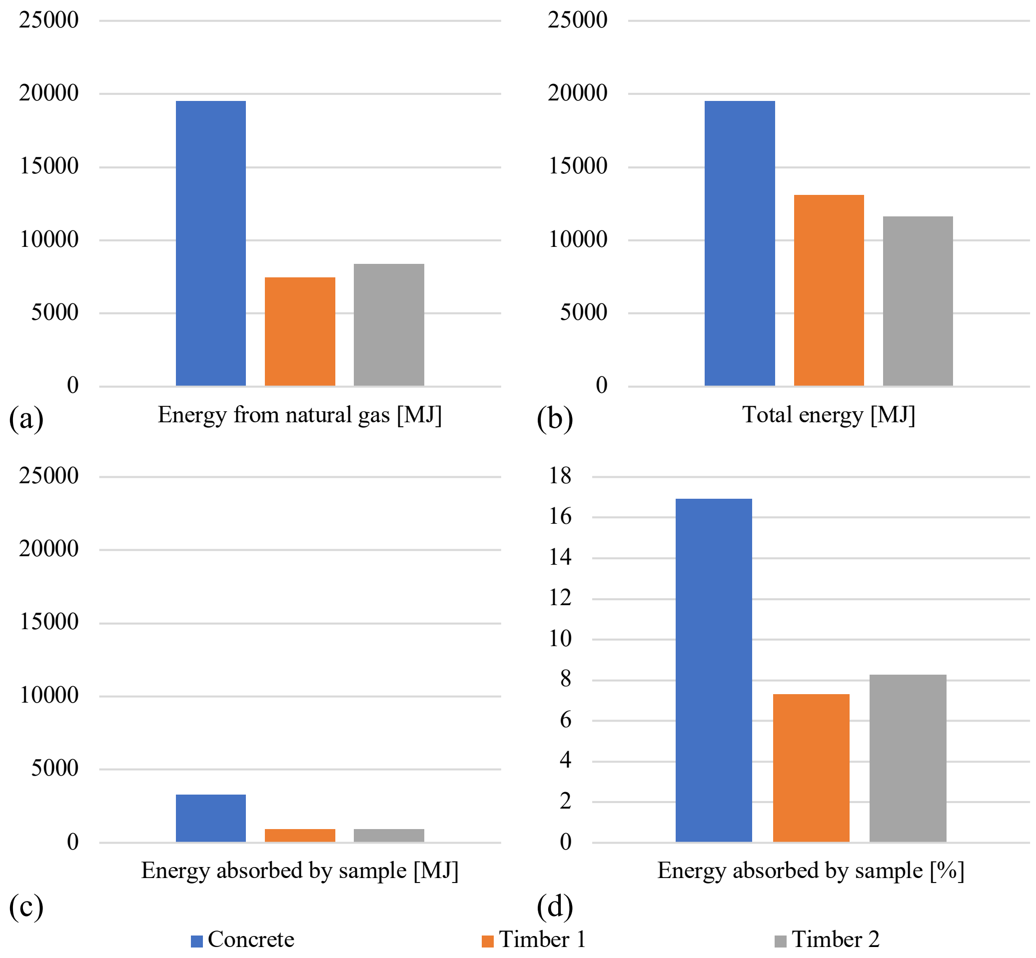

Figure 8: Comparison of energy provided and absorbed between different furnace tests compared during the first 120 minutes of heating, showing (a) total energy supplied by the natural gas; (b) total energy supplied to the furnace including the combustion of the timber; (c) total energy absorbed by the samples; and (d) the percentage of energy absorbed by the samples relative to the total energy provided.

3.4. Summary

It is clear from the above data that there are several key similarities and differences between the two types of slab elements. In terms of heat fluxes, for the configurations and materials tested herein:

- The plate thermometer temperature is the same for both concrete and CLT tests, which is not at all surprising given that this is what controls the furnace. Therefore the *net total* heat flux to the samples can be said to be similar [13] .
- The *absorbed* heat flux by the sample is around 3.5 times greater for concrete than for timber. This is due to the differences in thermal inertia and external energy supply to the sample.

In terms of energy:

- The *total* energy supplied to the furnace is around 1.5 to 2 times greater for concrete than for timber.
- The *external* energy supplied is around 2.5 to 3 times greater for concrete than for timber.

If the safety requirements of a real building are considered, it is evident that the *external* energy supplied to a fire must be amongst the variables of interest. This will undoubtedly influence the fire behaviour in terms of the gas temperatures, burning durations, and thus the incident and absorbed heat fluxes experienced by an element of structure during a real building fire. This ought to be explicitly considered by structural fire engineering designers.

4. Compartment Fire Experiments

To this end, a series of six large scale compartment fire experiments was performed to explore the differences in fire behaviour between combustible and non-combustible materials when the *external* energy supplied (i.e. compartment fuel load, not considering the structure itself) was fixed. The test specimens were installed on top of the compartment as a ceiling panel.

In each experiment, the external fuel load was supplied using wood cribs, with six cribs, each with 12 rows of five sticks. Each stick measured 90 mm x 90 mm x 1 m, and weighed approximately 3.5 kg. Thus the total external fuel load was approximately 22155 MJ, comparable to the external fuel load supplied during the first 120 minutes of the concrete furnace test (assuming complete combustion).

Three different opening factors were explored with one CLT panel and one concrete panel tested for each. Scenario 1 had a single, large opening, 5 m wide x 2 m tall. This was designed to allow an excess of oxygen in the room (i.e. a fuel-controlled condition, for combustion of the cribs alone). Scenario 2 had three openings, each 1.25 m wide x 1.2 m high, 1 m above the floor. This was designed to provide approximately sufficient oxygen (just) for stoichiometric burning of the cribs. Scenario 3 had a single opening, 1.1 m wide x 2 m high. This was designed to have limited oxygen within the compartment and deliver a clearly ventilation-controlled scenario. The total compartment dimensions were 5.9 m wide x 3.9 m deep x 2.5 m tall – i.e. approximately the same internal dimensions as the furnace used for the tests described previously in this paper. A photo of Scenario 1 is shown in Figure 9.

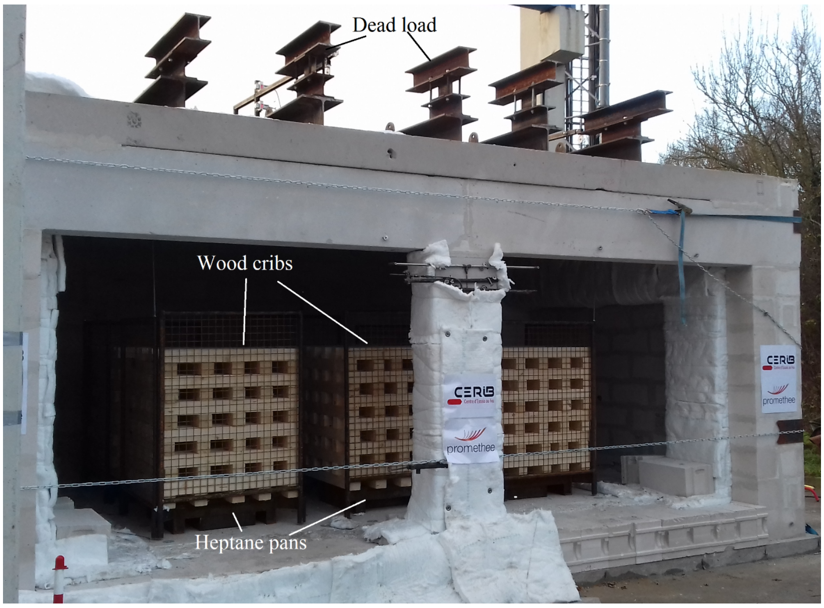

Figure 9: Photograph of concrete compartment Scenario 1, with mechanical and fire loads highlighted.

The cribs were ignited using a 3 L heptane pool fire beneath each crib. Temperatures were recorded using plate thermometers at a distance of 100 mm from the test specimen, as was the case in the fire testing furnace; these are presented in Figure 10. Fifteen plate thermometers were positioned 100 mm below the fire-exposed surface, spread out along the test specimen the to follow the measurement density used in standard furnace testing according to EN 1363-1 [3]and EN 1365-2 [14].

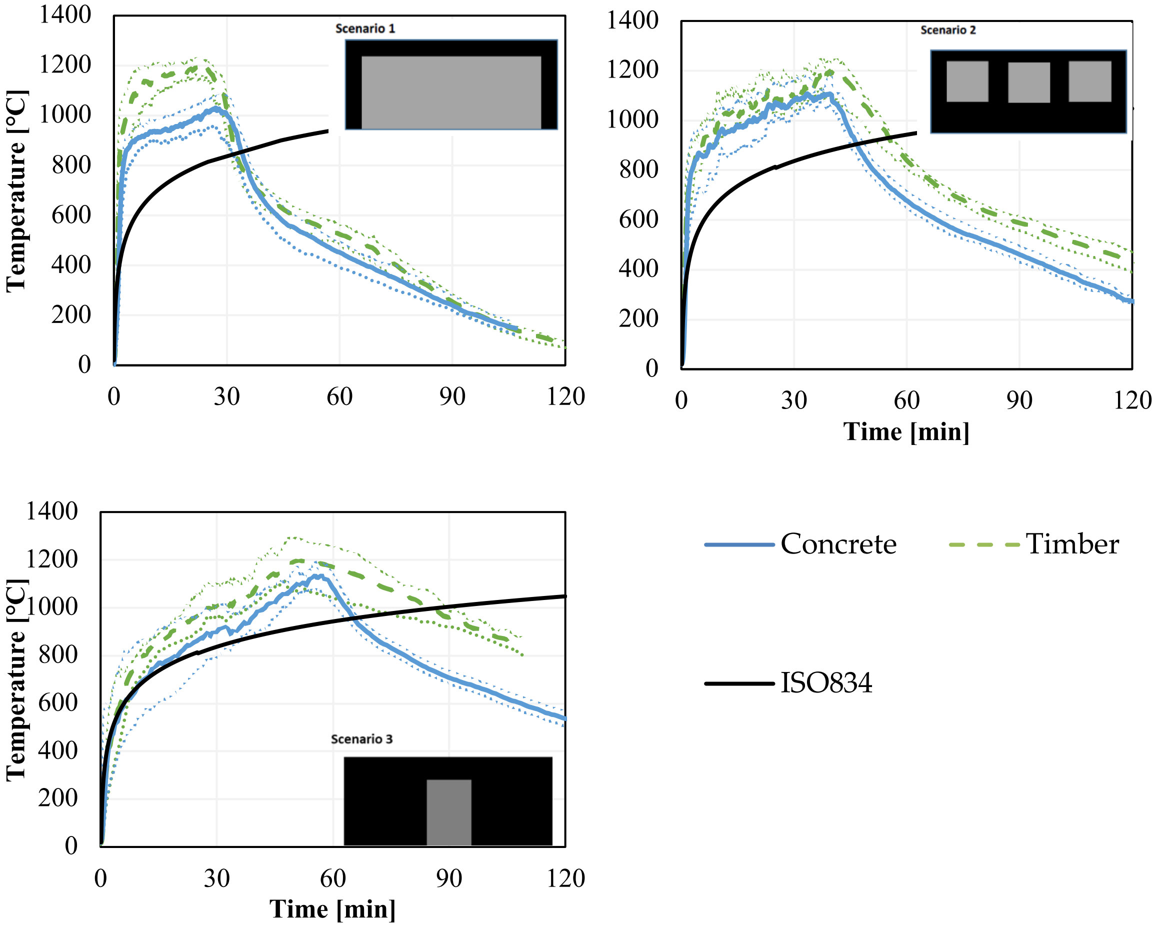

Figure 10: Averaged plate thermometer temperatures during compartment fire experiments, with minima and maxima shown. Top-left: Scenario 1 (large opening), top-right: Scenario 2 (three small openings); bottom-left: Scenario 3 (single small opening).

It can be seen from Figure 10 that in the case of fuel-controlled burning (large openings), the temperature is around 200°C higher when testing a timber slab than when testing a concrete slab. This is consistent with the findings from the furnace tests in that the timber slab is providing additional energy. In the case of ventilation-controlled burning (small openings), the temperatures are approximately the same, however the timber experiment has a heating phase around 10% longer.

This suggests that in a real fire, where the external fuel load would presumably be the same whether the construction is combustible or non-combustible, the plate thermometer temperature (and thus incident heat flux to the sample) and fire duration depend on the material properties of the test sample. This is in direct contrast to standard furnace testing, where plate thermometer temperatures and fire durations are explicitly prescribed.

5. Discussion

The results presented above show that the fundamentally different materials tested under the 'same' temperature versus time curves within a plate thermometer-controlled standard fire testing furnace do not experience the same energy input if the quantity of fuel available to the 'fire' is used as the comparative metric; as would be the case in a real building where a fire occurs based on natural physics, rather than by explicit control of fuel supply. In the experiments presented herein, the exposed CLT slab is exposed to an approximately 1 MW 'external' energy source, whereas the concrete sample is exposed to an approximately 3 MW external energy source. Additional energy contributions from the burning timber, as well as differences in thermal inertia of the two materials, result in the same furnace temperature being measured in both cases by the plate thermometers used to control the supply of fuel (natural gas in this case).

Quantification of the energy released by the timber in the furnace tests is subject to considerable uncertainties, due in part to uncertainties relating to the combustion efficiency of the timber. The energy released by a CLT slab is thus strongly dependent on the oxygen concentration inside the compartment (or furnace), which is dictated by the opening geometry. In a furnace, the oxygen supply is not controlled, and thus the rate of burning of a combustible test specimen will be very different in a furnace than in a real building (even if the burning rate of the external fuel load is the same). Whilst this is not an issue for non-combustible specimens, the thermal exposure (in intensity or duration) of a combustible specimen may vary significantly (as seen in the compartment fire experiments), and thus it is potentially important to consider the effects of fire dynamics when testing combustible specimens, particularly when the structural elements become involved in the combustion processes.

During the compartment fire experiments, it was observed that the CLT slabs continued to combust (through surface oxidation) for several hours after burnout of the compartment fuel load. This is consistent with findings from previous compartment fire experiments [8,15]. This observation may have important implications for the fire resistance design of both encapsulated and unprotected mass timber elements as when testing combustible materials, they may continue burning without added fuel if no immediate active fire intervention is made. Implicit in the traditional fire resistance ratings conventionally required for most building elements is the ability to withstand burnout of the fuel load within the compartment of origin [16]. In the case when the structure itself continues to burn, the traditional fire resistance rating has little meaning when related to the fuel load present within the compartment (as per the original intent [16]). Fire safety engineering professionals therefore ought to explicitly consider the implications of the above for the fire resistance design of structures that incorporate combustible structural elements, in order to ensure that both explicit (i.e. regulated) and implicit (i.e. expected/perceived) performance objectives in case of fire are openly discussed, and subsequently addressed, by their designs.

6. Conclusions

A series of standard fire resistance tests have demonstrated that the total energy to which a test specimen is 'exposed' within a fire testing furnace is significantly different depending on the material tested. This can be attributed in part to any additional energy contribution from combustible test specimens, and in part to differences in thermal diffusivity amongst the test elements themselves, thus resulting in different amounts of energy being absorbed by the samples. This may have important implications for the fire resistance design of real buildings, where the external energy supplied to a fire (by the compartment contents) must be assumed to be the same regardless of the construction material from which the structural frame is constructed. The additional energy generated from combustible test specimens has been shown herein to contribute to the energy inside the furnace (and thus reduce the external energy required to heat the furnace to the target temperature).

A complementary series of large scale compartment fire experiments has confirmed that, for the same external fuel load, temperatures and fire duration are considerably different if the test specimen (compartment ceiling in this case) is combustible. The fire temperatures and duration were also (unsurprisingly) different depending on the ventilation conditions; these dictate the availability of oxygen and thus how much fuel can burn (i.e. how much energy can be released) inside (versus outside) the compartment. This is not currently considered in standard fire resistance testing, but with the potential for exposed CLT panels to ignite and burn, consideration of the fire dynamics is essential to understand and quantify the additional energy generation (and subsequent in-depth temperatures and strength reductions) from the exposed panel.

This also has potentially important implications for external flaming and hence external fire spread, both over and between buildings; companion papers will address this issue separately.

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